

Stellar Archaeology — Exploring the Universe with Metal-Poor Stars

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The abundance patterns of the most metal-poor stars in the Galactic halo and small dwarf galaxies provide us with a wealth of information about the early Universe. In particular, these old survivors allow us to study the nature of the first stars and supernovae, the relevant nucleosynthesis processes responsible for the formation and evolution of the elements, early star- and galaxy formation processes, as well as the assembly process of the stellar halo from dwarf galaxies a long time ago. This review presents the current state of the field of “stellar archaeology” – the diverse use of metal-poor stars to explore the high-redshift Universe and its constituents. In particular, the conditions for early star formation are discussed, how these ultimately led to a chemical evolution, and what the role of the most iron-poor stars is for learning about Population III supernovae yields. Rapid neutron-capture signatures found in metal-poor stars can be used to obtain stellar ages, but also to constrain this complex nucleosynthesis process with observational measurements. Moreover, chemical abundances of extremely metal-poor stars in different types of dwarf galaxies can be used to infer details on the formation scenario of the halo, and the role of dwarf galaxies as Galactic building blocks. I conclude with an outlook as to where this field may be heading within the next decade. A table of ~ 1000 metal-poor stars and their abundances as collected from the literature is provided in electronic format.

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1 Introduction

As Carl Sagan once remarked, *If you wish to make an apple pie from scratch, you must first create the Universe.* An apple contains at least 16 different elements¹, and the human body is even more complex, having at least trace amounts of nearly 30 elements², all owing to a 14-billion year long manufacturing process called cosmic chemical evolution. Thus, the basis of chemically complex and challenging undertakings such as cooking and baking, not to mention the nature of life, will ultimately be gained through an understanding of the formation of the elements that comprise organic material. It is thus important to examine how the constituents of an apple, and by extension the stuff of life and the visible Universe were created: baryonic matter in the form of elements heavier than primordial hydrogen and helium. In this review I will describe how the chemical abundances observed in the most metal-poor stars are employed to unravel a variety of details about the young Universe, such as early star formation, nucleosynthesis in stars and supernovae (SNe), and the formation process(es) of the Galactic halo. This concept is often called “stellar archaeology” and is frequently used to address a number of important, outstanding questions:

- What is the nature of Pop III stars? Are the yields of the first SNe different from today’s? Can we find the signatures of theorized pair-instability SNe?
- What drove early star formation? How/where did the first low-mass stars and the first galaxies form?
- What are the main nucleosynthesis processes and sites that are responsible for forming the elements from the Big Bang until today?
- How did chemical evolution proceed? How do stellar chemistry and halo kinematics correlate? How can we use abundances to learn about the halo formation process?
- Was the old halo built from accreted satellites? Can we identify accreted dwarf galaxies in the halo? Did the first stars form in dwarf galaxies?

Even though some of these questions appear to refer to completely unrelated topics, metal-poor stars do provide us with a powerful tool to study a very broad range of astrophysical issues ranging from nuclear astrophysics to early galaxy formation. Metal-poor stars represent the local equivalent to the high-redshift Universe, and thus provide a unique tool to address a wide range of near and far-field cosmological topics.

Each section of this review discusses one of those topics and can be read independently, although it is advisable to also peruse Section 2. It sets the overall stage by introducing the first stars, early low-mass star formation and whether stellar archaeology is a valid concept to study the

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¹ [http://www.food-allergens.de/symposium-vol1\(3\)/data/apple/apple-composition.htm](http://www.food-allergens.de/symposium-vol1(3)/data/apple/apple-composition.htm)

² <http://chemistry.about.com/cs/howthingswork/f/blbodyelements.htm>

high-redshift Universe. Section 3 then discusses the most iron-poor stars and their connection to early SNe, whereas in Section 4, the observed signatures of neutron-capture nucleosynthesis are presented. In particular, the r-process and nucleo-chronometry are discussed. Section 5 deals with the metal-poor stars recently found in small dwarf galaxies and what we can learn from their chemical abundances about the early formation process of the Galactic halo. Conclusions and an outlook are given in Section 6.

Since there exist a large range of metal-poor stars in terms of their metallicities and chemical signatures, Beers & Christlieb (2005) suggested a classification scheme. In this review I will make extensive use of their term “extremely metal-poor stars”, referring to stars with $[\text{Fe}/\text{H}] < -3.0$. “Ultra metal-poor” then refers to $[\text{Fe}/\text{H}] < -4.0$, and “hyper metal-poor” to $[\text{Fe}/\text{H}] < -5.0$. This already shows that the main metallicity indicator used to determine any stellar metallicity is the iron abundance, $[\text{Fe}/\text{H}]$, which is defined as $[A/B] = \log_{10}(N_A/N_B)_* - \log_{10}(N_A/N_B)_\odot$ for the number N of atoms of elements A and B , and \odot refers to the Sun. With few exceptions, $[\text{Fe}/\text{H}]$ traces the overall metallicity of the objects fairly well.

2 The Early Universe

2.1 The First Stars

According to cosmological simulations that are based on the Λ cold dark matter model of hierarchical structure growth in the Universe, the first stars formed in small minihalos some few hundred million years after the Big Bang. Due to the lack of cooling agents in the primordial gas, significant fragmentation was largely suppressed so that these first objects were very massive (of the order to $\sim 100 M_\odot$; e.g. Bromm & Larson 2004 and references therein). This is in contrast to low-mass stars dominating today’s mass function. These objects are referred to as Population III (Pop III) as they formed from metal-free gas.

These objects soon exploded as SNe to either collapse into black holes (progenitor masses of $25 < M_\odot < 140$ and $M_\odot > 260$) or to die as energetic pair-instability SNe (PISN; $140 < M_\odot < 260$; Heger & Woosley 2002). During their deaths, these objects provided vast amounts of ionizing radiation (and some of the first metals in the case of the PISNe) that changed the conditions of the surrounding material for subsequent star formation even in neighboring minihalos. Hence the second generation of stars might have been less massive ($M_* \sim 10 M_\odot$). Partially ionized gas supports the formation of the H_2 , and then the HD molecule which in turn facilitates more effective cooling than what is possible in neutral gas. Also, any metals or dust grains left behind from PISNe would have similar cooling effects. This may then have led to the first more regular metal-producing SNe, although not all higher mass SNe must necessarily end in black hole formation. Umeda & Nomoto (2003) suggested that some $25 M_\odot$ stars undergo only a partial fallback, so that some of the newly created metals get ejected

into the surrounding gas. By that time, most likely enough metals were present to ensure sufficient gas fragmentation to allow for low-mass ($< 1 M_\odot$) star formation. Those stars that formed from any metal-enriched material are referred to as Population II (Pop II) stars. More metal-rich stars like the Sun that formed in a much more metal-rich Universe are called Population I.

The concept of stellar archaeology entails that the most extreme versions of Pop II stars preserve in their surface composition the individual SN yields of previous Pop III stars. Studying those “chemical fingerprints” in the oldest, most metal-poor stars can thus reveal a great deal about the first nucleosynthesis events in the Universe. Indeed, several metal-poor star abundance patterns have been fitted with calculated Pop III SN yields. Moreover, one may also seek to find a PISN signature (a pronounced odd-even abundance signature) in metal-poor stars. This has, however, not yet occurred.

2.2 Early low-mass star formation and the connection to carbon-enhanced metal-poor stars

Early Pop II stars began to form from the enriched material left behind by the first stars. The actual formation process of these initial low-mass ($M \leq 0.8 M_\odot$) Pop II stars (i.e. the most metal-poor stars) that live longer than a Hubble time, is not well-understood so far. Ideas for the required cooling processes necessary to induce sufficient fragmentation of the near-primordial gas include cooling through metal enrichment (“critical metallicity”) or dust, cooling based on enhanced molecule formation due to ionization of the gas, as well as more complex effects such as turbulence and magnetic fields (Bromm et al. 2009).

Fine-structure line cooling through neutral carbon and singly-ionized oxygen has been suggested as a main cooling agent facilitating low-mass star formation (Bromm & Loeb 2003). These elements were likely produced in vast quantities in Pop III objects (e.g. Meynet et al. 2006a). Gas fragmentation is then induced once a critical metallicity of the interstellar medium (ISM) is achieved. The existence of such a critical metallicity can be probed with large numbers of carbon and oxygen-poor metal-poor stars. Frebel et al. (2007b) developed an “observer-friendly” description of the critical metallicity that incorporates the observed C and/or O stellar abundances; $D_{\text{trans}} = \log(10^{[\text{C}/\text{H}]} + 0.3 \times 10^{[\text{O}/\text{H}]}) \geq -3.5$. Any low-mass stars still observable today then has to have C and/or O abundances above the threshold of $D_{\text{trans}} = -3.5$ (see Figure 1 in Frebel et al. 2007b). At metallicities of $[\text{Fe}/\text{H}] \gtrsim -3.5$, most stars have C and/or O abundances that are above the threshold since they follow the solar C and O abundances simply scaled down to their respective Fe values. Naturally, this metallicity range is not suitable for directly probing the first low-mass stars. Below $[\text{Fe}/\text{H}] \sim -3.5$, however, the observed C and/or O levels must be higher than the Fe-scaled solar abundances to be above the critical metallicity. Indeed, none of the known lowest-metallicity stars has a D_{trans} below the critical

value, consistent with this cooling theory. Some stars, however, have values very close to $D_{\text{trans}} = -3.5$. HE 0557–4840, at $[\text{Fe}/\text{H}] = -4.75$ (Norris et al. 2007), falls just onto the critical limit (M. Bessell 2009, priv. comm.). A star in the ultra-faint dwarf galaxy Boötes I has $D_{\text{trans}} = -3.2$ (at $[\text{Fe}/\text{H}] = -3.7$; and assuming that its oxygen abundance is twice that of carbon). An interesting case is also the most metal-poor star in the classical dwarf galaxy Sculptor, which has an upper limit of carbon of $[\text{C}/\text{H}] < -3.6$ at $[\text{Fe}/\text{H}] = -3.8$ (Frebel et al. 2009b). Despite some still required up-correction of carbon to account for atmospheric carbon-depletion of this cool giant, the star could potentially possess a sub-critical D_{trans} value.

Overall, more such “borderline” examples are crucial to test for the existence of a critical metallicity. If fine-structure line cooling were the dominant process for low-mass star formation, two important consequences would follow: 1) Future stars to be found with $[\text{Fe}/\text{H}] \lesssim -4.0$ are predicted to have these significant C and/or O overabundances with respect to Fe. 2) The so-far unexplained large fraction of metal-poor objects that have large overabundances of carbon with respect to iron ($[\text{C}/\text{Fe}] > 1.0$) may reflect an important physical cause. About 20% of metal-poor stars with $[\text{Fe}/\text{H}] \lesssim -2.5$ exhibit this behavior (e.g. Beers & Christlieb 2005). Moreover, at the lowest metallicities, this fraction is even higher. All three stars with $[\text{Fe}/\text{H}] < -4.0$ are extremely C-rich, well in line with the prediction of the line cooling theory.

It should also be mentioned that cooling through dust grains might have been responsible for the transition from Pop III to Pop II star formation. Dust created during the first SNe explosions or mass loss during the evolution of Pop III stars may induce fragmentation processes (e.g., Schneider et al. 2006) that lead to the formation of subsolar-mass stars. The critical metallicity in this scenario is a few orders of magnitude below that of C and O line cooling. If some metal-poor stars are found to be below $D_{\text{trans}} = -3.5$, they may still be consistent with the critical value set by dust cooling.

2.3 Validating Stellar Archaeology

Stellar archaeology is based on long-lived low-mass metal-poor main-sequence and giant stars whose chemical abundances are thought to reflect the composition of the ISM during their formation. A vital assumption is that the stellar surface compositions have not been significantly altered by any internal mixing processes given that these stars are fairly unevolved despite their old age. But are there other means by which the surface composition could be modified? Accretion of interstellar matter while a star orbits in the Galaxy for ~ 10 Gyr has long been suggested as a mechanism to affect the observed abundance patterns. Iben (1983) calculated a basic “pollution limit” of $[\text{Fe}/\text{H}] = -5.7$ based on Bondi-Hoyle accretion. He predicted that no stars with Fe abundances below this value could be found since they would have accreted too much enriched material.

Assuming that stars with such low-metallicities exist (for example low-mass Pop III stars if the IMF was Salpeter-like, and not top-heavy), significant amounts of interstellar accretion could masquerade the primordial abundances of those putative low-mass Pop III stars. Analogously, stars with very low abundances, say $[\text{Fe}/\text{H}] < -5.0$, could principally be affected also. Frebel et al. (2009a) carried out a kinematic analysis of a sample of metal-poor stars to assess their potential accretion histories over the past 10 Gyr in a Milky Way-like potential. The amount of accreted Fe was calculated based on the total accreted material over 10 Gyr. The overall chemical evolution with time was taken into account assuming the ISM to have scaled solar abundances.

The stellar abundances were found to be little affected by accretion. The calculated, “accreted abundances” were often lower than the observed measurements by several orders of magnitude. Generally, this confirms that accretion does not significantly alter the observed abundance patterns, even in an extreme case in which a star moves once through a very large, dense cloud. The concept of stellar archaeology is thus viable. Nevertheless, since there is a large accretion dependency on the space velocity it becomes obvious that kinematic information is vital for the identification of the lowest-metallicity stars in the Milky Way and the interpretation of their abundances.

2.4 The metallicity distribution function

Large numbers of Galactic metal-poor stars found in objective-prism surveys in both hemispheres have provided great insight into the history and evolution of our Galaxy (e.g., Beers & Christlieb 2005). However, there are still only very few stars known ($\lesssim 20$) with metallicities below $[\text{Fe}/\text{H}] < -3.5$. Recently, Schörck et al. (2009) presented a new metallicity distribution function (MDF) for halo stars that is corrected for various selection effects and other biases. The number of known metal-poor stars declines significantly with decreasing metallicity (below $[\text{Fe}/\text{H}] < -2.0$) as illustrated in their Figures 10 and 18. The new bias-corrected MDF also shows how rare metal-poor stars really are, but also that past targeted (“biased”) searches for metal-poor stars have been extremely successful at identifying these objects. The biggest achievements in terms of the most iron-deficient stars was the push to a significantly lower stellar metallicity $[\text{Fe}/\text{H}]$ almost a decade ago: From a longstanding $[\text{Fe}/\text{H}] = -4.0$ (CD –38° 245; Bessell & Norris 1984) to $[\text{Fe}/\text{H}] = -5.2$ (HE 0107–5240; Christlieb et al. 2002³), and more recently, down to $[\text{Fe}/\text{H}] = -5.4$ (HE 1327–2326; Frebel et al. 2005). Overall, only three stars are known with iron abundances of $[\text{Fe}/\text{H}] < -4.0$. The recently discovered star HE 0557–4840 (Norris et al. 2007) with $[\text{Fe}/\text{H}] < -4.8$ bridges the gap between $[\text{Fe}/\text{H}] = -4.0$ and the two hyper Fe-poor objects. Ob-

³ Applying the same non-LTE correction to the Fe I abundances of HE 0107–5240 and HE 1327–2326 leads to a final abundance of $[\text{Fe}/\text{H}] = -5.2$ for HE 0107–5240.

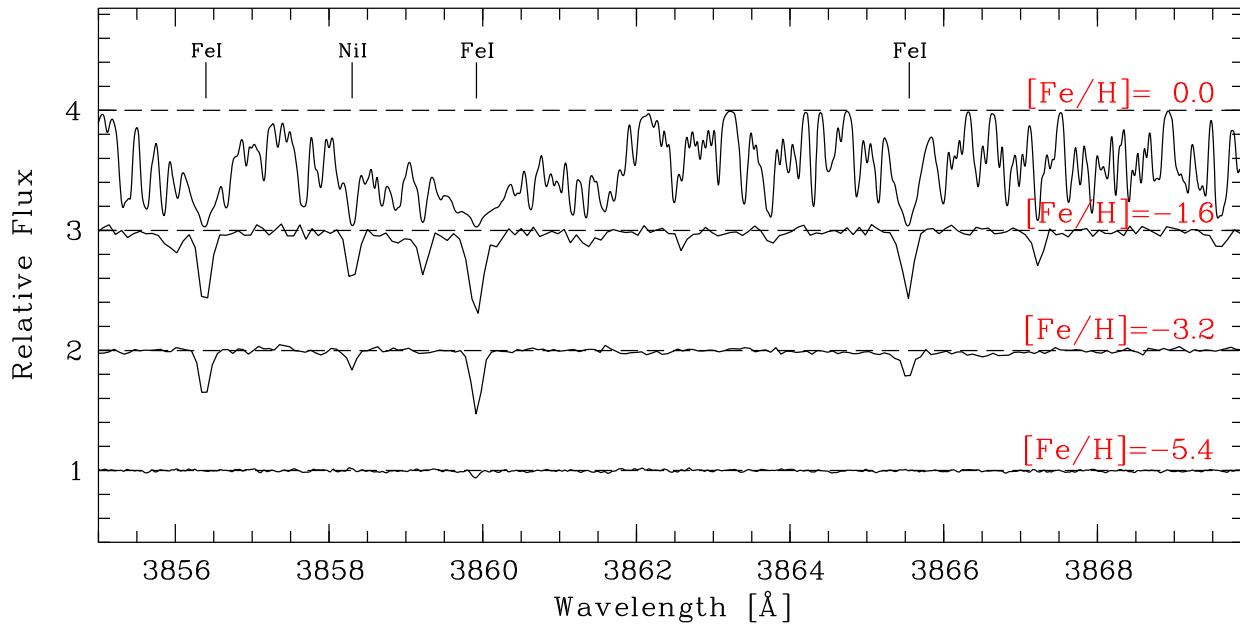


Fig. 1 Spectral comparison of stars in the main-sequence turn-off region with different metallicities. Several absorption lines are marked. The variations in line strength reflect the different metallicities. From top to bottom: Sun with $[\text{Fe}/\text{H}] = 0.0$, G66-30 $[\text{Fe}/\text{H}] = -1.6$ (Norris et al. 1997c), G64-12 $[\text{Fe}/\text{H}] = -3.2$ (Frebel et al. 2005), and HE1327-2326 $[\text{Fe}/\text{H}] = -5.4$ (Frebel et al. 2005).

jects in the very tail of the MDF provide a unique observational window onto the time very shortly after the Big Bang. They provide key insights into the very beginning of Galactic chemical evolution.

To illustrate the progression of metallicity from metal-rich to the most metal-poor stars, Figure 1 shows spectra around the strongest optical Fe line at 3860 Å of the Sun and four other metal-poor main-sequence stars. The number of atomic absorption lines detectable in the spectra decreases with increasing metal-deficiency. In HE 1327–2326, only the intrinsically strongest metal lines remain observable, and these are extremely weak. If a main-sequence star with even lower Fe value was discovered, no Fe lines would be measurable anymore. In the case of a giant, the lines would be somewhat stronger due to its cooler temperature and thus allow for the discovery of a $[\text{Fe}/\text{H}] \lesssim -6$ object.

3 Studying the Early Universe with Metal-Poor Stars

3.1 Searching for the Most Metal-Poor Stars

Over the past two decades, the quest to find the most metal-poor stars to study the chemical evolution of the Galaxy led to a significant number of stars with metallicities down to $[\text{Fe}/\text{H}] \sim -4.0$ (see Beers & Christlieb 2005 for a more detailed review). Those stars were initially selected as candidates from a large survey, such as the HK survey (Beers et al. 1992) and the Hamburg/ESO survey (Wisotzki et al. 1996). A large survey is required to provide numerous low-resolution

spectra to search for weak-lined stellar candidates. Those spectra have to cover the strong Ca II K line at 3933 Å because the strength of this line indicates the metallicity of the star, and can be measured in low-quality spectra. If this line is sufficiently weak as a function of the star's estimated effective temperature, an object is selected as a candidate metal-poor star. For all candidates, medium-resolution spectra ($R \sim 2000$) are required to more accurately determine the

Ca II K line strength for a more robust estimate for the Fe abundance. This line is still the best indicator for the overall metallicity $[\text{Fe}/\text{H}]$ of a metal-poor star in such spectra. In the Sloan Digital Sky Survey and LAMOST survey, the survey spectra themselves are already of medium-resolution allowing for a quicker and more direct search for metal-poor stars. To confirm the metallicity, and to measure elemental abundances from their respective absorption lines besides that of iron, high-resolution optical spectroscopy is required. Only then the various elements become accessible for studying the chemical evolution of the Galaxy. Those elements include carbon, magnesium, calcium, titanium, nickel, strontium, and barium, and trace different enrichment mechanisms, events and timescales. Abundance ratios $[\text{X}/\text{Fe}]$ as a function of $[\text{Fe}/\text{H}]$ can then be derived for the lighter elements ($Z < 30$) and neutron-capture elements ($Z > 38$). The final number of elements hereby depends on the type of metal-poor star, the wavelength coverage of the data, and the data quality itself.

3.2 Chemical Evolution of the Galaxy

Generally, there are several main groups of elements observed in metal-poor stars, with each group having a common, main production mechanism; 1) α -elements (e.g. Mg, Ca, Ti) are produced through α -capture during various burning stages of late stellar evolution, before and during SN explosions. These yields appear very robust with respect to parameters such as mass and explosion energy 2) Fe-peak elements ($23 < Z < 30$) are synthesized in a host of different nucleosynthesis processes before and during SN explosions such as radioactive decay of heavier nuclei or direct synthesis in explosive burning stages, neutron-capture onto lower-mass Fe-peak elements during helium and later burning stages and alpha-rich freeze-out processes. Their yields also depend on the explosion energy; 3) Light and heavy neutron-capture elements ($Z > 38$) are either produced in the slow (s-) process occurring in thermally pulsing AGB stars (and then transferred to binary companions or deposited into the ISM through stellar winds) or in the rapid (r-) process most likely occurring in core-collapse SN explosions. For more details on SN nucleosynthesis see e.g., Woosley & Weaver (1995).

The α -element abundances in metal-poor halo stars with $[\text{Fe}/\text{H}] \sim -1.5$ are enhanced by ~ 0.4 dex with respect to Fe (see Figure 2). This reflects a typical core-collapse SN signature because at later times (in chemical space at about $[\text{Fe}/\text{H}] \sim -1.5$) the onset of SN Ia provides a significant contribution to the overall Galactic Fe inventory. As a consequence, the $[\alpha/\text{Fe}]$ ratio decreases down to the solar value at $[\text{Fe}/\text{H}] \sim 0.0$. The general uniformity of light element abundance trends down to $[\text{Fe}/\text{H}] \sim -4.0$ led to the conclusion that the ISM must have been already well-mixed at very early times (Cayrel et al. 2004). Otherwise it would be hard to understand why so many of the most metal-poor stars have almost identical abundance patterns. However, despite the well-defined abundance trends, some stars, particularly those in the lowest metallicity regime show significant deviations. Some stars have been found to be very α -poor (e.g. Ivans et al. 2003) and others are strongly overabundant in Mg and Si (e.g., Aoki et al. 2002b; Frebel et al. 2005).

Among the Fe-peak elements, many have subsolar abundance trends at low metallicity (e.g. $[\text{Cr}, \text{Mn}/\text{Fe}]$) which become solar-like as the metallicity increases (see Figure 3). It is not clear whether these large underabundances are of cosmic origin or have to be attributed to modelling effects such as that of non-LTE (Bergemann & Gehren 2008; Sobeck et al. 2007). Trends of other elements are somewhat overabundant at low metallicity (Co) or relatively unchanged throughout (Sc, Ni). All elements with $Z < 30$ hereby have relatively tight abundance trends.

How can all those signatures be understood? The observed abundances of the most metal-poor stars with “classical” halo signatures have successfully been reproduced with Pop III SN yields. Tominaga et al. (2007) model the averaged abundance pattern of four non-carbon-enriched stars with $-4.2 < [\text{Fe}/\text{H}] < -3.5$ with the elemental yields of

a massive, energetic ($\sim 30 - 50 M_{\odot}$) Pop III hypernova. The abundances can also be fitted with integrated yields of Pop III SNe Heger & Woosley (2008). Special types of SNe or unusual nucleosynthesis yields can then be considered for stars with chemically peculiar abundance patterns. It is, however, often difficult to explain the entire abundance pattern. Additional metal-poor stars as well as a better understanding of the explosion mechanism and the impact of the initial conditions on SNe yields are required to arrive at a more solid picture of exactly how metal-poor stars reflect early SNe yields.

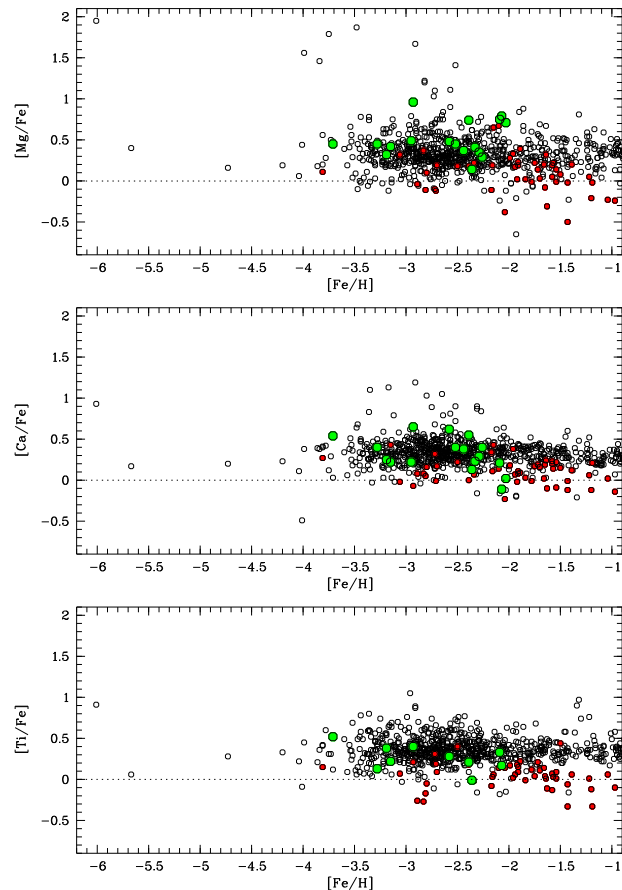


Fig. 2 Light element abundance trends of Mg, Ca, and Ti. Black open circles represent halo stars, red filled circles are stars in the classical dwarf galaxies, and green filled circles show stars in the ultra-faint dwarf galaxies. Both the x- and y-axis have the same scale for easy comparisons. Only stars with high-resolution abundance analyses are shown. The abundance data can be found in an electronic format. The scatter in the data likely reflects systematic differences between literature studies. Assuming this, systematic uncertainties in abundance analyses may be around ~ 0.3 dex.

On the contrary, the abundances of the neutron-capture elements in metal-poor stars are “all over the place”. Sr has an extremely large scatter (~ 3 dex). This indicates that different nucleosynthetic processes must have contributed

to its Galactic inventory, or that neutron-capture yields are very environmentally-sensitive. Ba has even more scatter at $[\text{Fe}/\text{H}] \sim -3.0$ (see Figure 4). Other heavier neutron-capture elements, such as Eu, have somewhat less scatter but this may be due to their generally weak and usually more difficult to detect absorption lines. What is apparent, though, is that at the lowest metallicities, core-collapse SNe must have dominated the chemical evolution (below $[\text{Fe}/\text{H}] = -3.0$).

Hence, the r-process is responsible for the neutron-capture elements at this early time. The s-process contribution occurred at somewhat later times, driven by the evolutionary timescales of stars with $\sim 2\text{--}8 M_{\odot}$ to become AGB stars.

To illustrate the extent of the chemical evolution of the Galaxy we have collected abundance data of metal-poor stars from the literature (Figures 2, 3 and 4). All abundances $[\text{X}/\text{Fe}]$ have been recalculated with the latest solar abundances of Asplund et al. (2009). In the many cases where a star has been studied more than once, the study with the most elements (i.e. likely with the highest quality data) was usually picked. No other processing of the literature data has been done. Hence, systematic differences between different studies remain. The tables containing all the abundances are easily accessible from the website of the Astronomische Nachrichten (www.aip.de/AN/). Abundance plots for all elements, the corresponding tables and more explanations are available at

www.cfa.harvard.edu/~afrebel/abundances/abund.html References are assigned to each set of abundances in the table. They are also alphabetically listed in the Appendix. For many stars, a key tag has been assigned to each star corresponding to its chemical properties. The keys are listed on the website as well. A similar collection of data can be found in the SAGA database (Suda et al. 2008) which is independent of the current collection.

3.3 The most iron-poor stars

The first star with a record-low iron abundance was found in 2001. The faint ($V = 15.2$) red giant HE 0107–5240 has $[\text{Fe}/\text{H}] = -5.2$ (Christlieb et al. 2002). In 2004, the bright ($V = 13.5$) subgiant HE 1327–2326 was discovered (Aoki et al. 2006b; Frebel et al. 2005). HE 1327–2327 has an even lower iron abundance of $[\text{Fe}/\text{H}] = -5.4$. This value corresponds to $\sim 1/250,000$ of the solar iron abundance. Interestingly, the entire mass of iron in HE 1327–2326 is actually 100 times less than that in the Earth's core. At the same time the star is of course of the order of a million times more massive than the Earth. A third star with $[\text{Fe}/\text{H}] = -4.75$ (Norris et al. 2007) was found in 2006. The metallicity of the giant HE 0557–4840 is in between the two < -5.0 stars and the next most metal-poor stars are $[\text{Fe}/\text{H}] \sim -4.0$. Hence it sits right in the previously claimed “metallicity gap” (between $[\text{Fe}/\text{H}] \sim -4.0$ and $[\text{Fe}/\text{H}] \sim -5.0$; e.g. Shigeyama et al. 2003) showing that the scarcity of stars below $[\text{Fe}/\text{H}] = -4.0$ is not a physical cause but a merely an observational incompleteness. All three objects were found

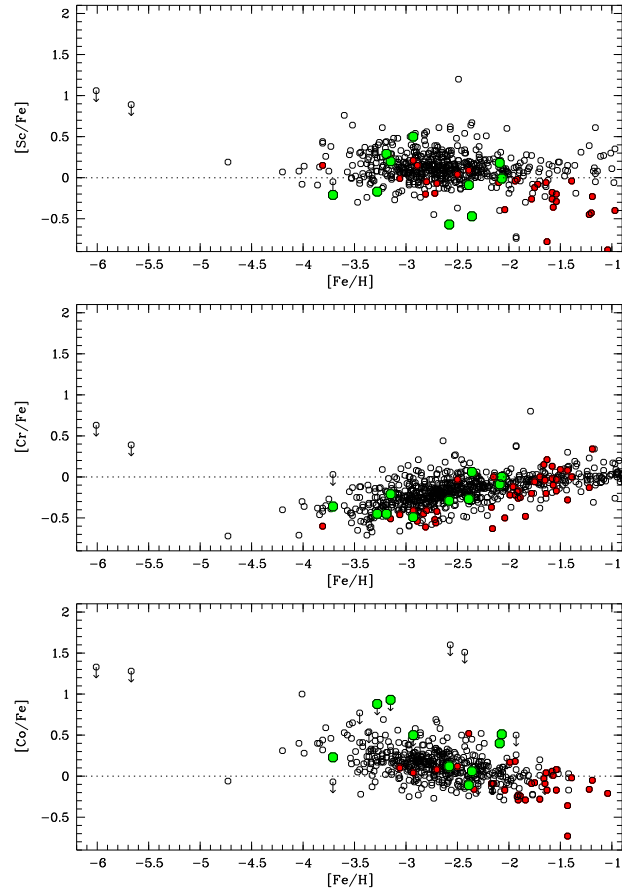


Fig. 3 Same as Figure 2, but for the Fe-peak elements Sc, Cr, and Co.

in the Hamburg/ESO survey making it the so far most successful database for metal-poor stars.

The most striking features in both < -5.0 stars are the extremely large overabundances of CNO elements. HE 0557–4840 partly shares this signature by also having a fairly large $[\text{C}/\text{Fe}]$ ratio. Other elemental ratios $[\text{X}/\text{Fe}]$ are somewhat enhanced in HE 1327–2327 with respect to the stars with $-4.0 < [\text{Fe}/\text{H}] < -2.5$, but less so for the two giants. No neutron-capture element is detected in HE 0107–5240 or HE 0557–4840, whereas, unexpectedly, Sr is observed in HE 1327–2326. The Sr may originate from the neutrino-induced νp -process operating in SN explosions (Fröhlich et al. 2006). Despite expectations, Li could not be detected in the relatively unevolved subgiant HE 1327–2326. The upper limit is $\log \epsilon(\text{Li}) < 1.6$, where $\log \epsilon(\text{A}) = \log_{10}(N_{\text{A}}/N_{\text{H}}) + 12$. This is surprising, given that the primordial Li abundance is often inferred from similarly unevolved metal-poor stars (Ryan et al. 1999). Furthermore, the upper limit found from HE 1327–2326, however, strongly contradicts the WMAP value ($\log \epsilon(\text{Li}) = 2.6$) from the baryon-to-photon ratio (Spergel et al. 2007). This may indicate that the star formed from extremely Li-poor material.

HE 0107–5240 and HE 1327–2326 immediately became benchmark objects to constrain various theoretical

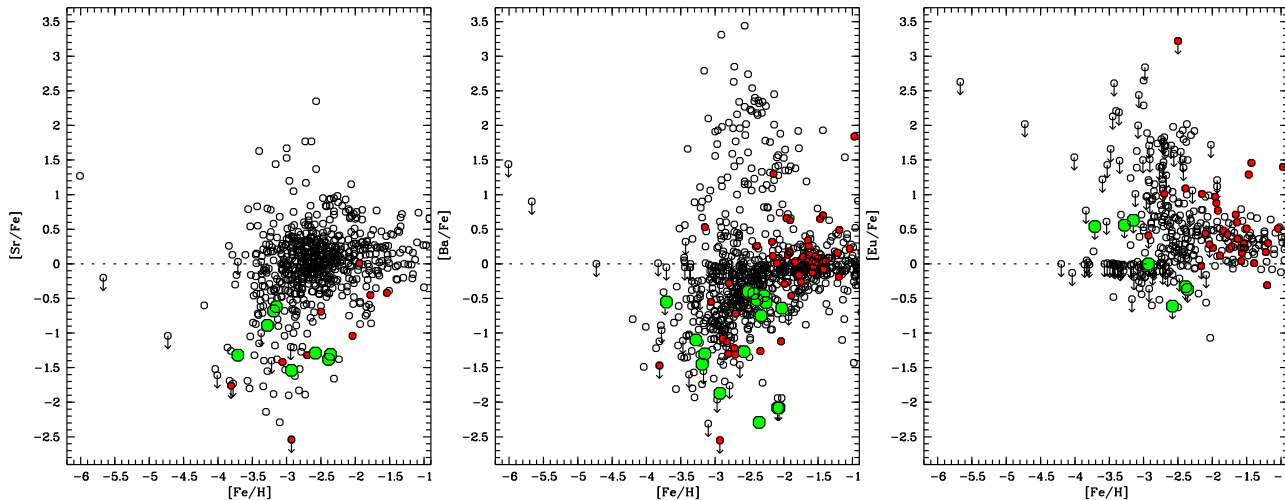


Fig. 4 Same as Figure 2, but for the neutron-capture elements Sr, Ba, and Eu. For these elements, the scatter is much beyond systematic differences between individual studies and thus indicates a cosmic origin.

studies of the early Universe, such as the formation of the first stars (e.g., Yoshida et al. 2006), the chemical evolution of the early ISM (e.g., Karlsson & Gustafsson 2005) or calculations of Pop III SN yields. Their highly individual abundance patterns have been successfully reproduced by several different SNe scenarios. This makes HE 0107–5240 and HE 1327–2326 early, extreme Pop II stars that possibly display the “fingerprint” of just one Pop III SN. Umeda & Nomoto (2003) first matched the yields of a faint $25 M_{\odot}$ SN that underwent a mixing and fallback process to the observed abundances of HE 0107–5240. To achieve a simultaneous enrichment of a lot of C and only little Fe, large parts of the Fe-rich SN ejecta have to fall back onto the newly created black hole. Using yields from a SN with similar explosion energy and mass cut, Iwamoto et al. (2005) then reproduced the abundance pattern of HE 1327–2326 also. Trying to fit the observed stellar abundances, Heger & Woosley (2008) are employing an entire grid of Pop III SN yields to search for the best match to the data. A similar progenitor mass range as the Umeda & Nomoto (2003) $25 M_{\odot}$ was found to be the best match to have provided the elemental abundances to the ISM from which these Pop II stars formed. Meynet et al. (2006b) explored the influence of stellar rotation on elemental yields of $60 M_{\odot}$ near-zero-metallicity SNe. The stellar mass loss rate of rotating massive Pop III stars qualitatively reproduces the CNO abundances observed in HE 1327–2326 and other carbon-rich metal-poor stars.

Limongi et al. (2003) were able to reproduce the abundances of HE 0107–5240 through pollution of the birth cloud by at least two SNe. Suda et al. (2004) proposed that the abundances of HE 0107–5240 would originate from a mass transfer of CNO elements from a postulated companion, and from accretion of heavy elements from the ISM. However, neither HE 0107–5240 nor HE 1327–2326 show radial velocity variations that would indicate binarity (R. Lunnan in preparation).

4 Neutron-Capture Nucleosynthesis Observed in Metal-Poor Stars

All elements heavier than the Fe-peak are created through neutron-capture processes in stars during stellar evolution (via AGB nucleosynthesis; slow *s*-process) and SN explosions (via the rapid *r*-process). We here summarize the most important constraints on the various neutron-capture processes provided by different types of metal-poor stars. A short review of *r*-process nucleosynthesis as observed in metal-poor stars can also be found in Frebel (2009). For a detailed review on how neutron-capture processes drove the chemical evolution of the Galaxy, we refer the interested reader to Sneden et al. (2008).

4.1 The *r*-Process Signature

The *r*-process occurs when a seed nucleus (e.g., a Fe or C nucleus) is under intensive neutron bombardment. In particular, when the neutron-capture rate exceeds that of the β -decay, large numbers of neutrons can be captured quickly to build up even the heaviest nuclei in the periodic table ($38 < Z < 92$). The astrophysical site(s) that can accommodate the required extreme environment for this process have not yet been clearly identified. Neutron-driven winds emerging from a proto-neutron-star which formed after a SN explosion (perhaps with a progenitor of $8 - 10 M_{\odot}$) seem to be promising locations (Qian & Wasserburg 2003). Neutron-star mergers have also been considered, but their long evolutionary timescales make them unsuitable as the primary *r*-process site in the early Galaxy (Argast et al. 2000). Not knowing the site, and hence, the initial conditions, makes it difficult to study the *r*-process theoretically. Furthermore, nuclear physics experiments on heavy, exotic *r*-process nuclei are technically out of reach. This leaves few experimental constraints on the production of the heaviest elements in the Universe.

Fortunately, about 5% of metal-poor stars with $[\text{Fe}/\text{H}] < -2.5$ contain a strong enhancement of neutron-capture element⁴ associated with the r-process (Beers & Christlieb 2005). In those stars, we can observe the majority of elements in the periodic table: the usual light, α - and iron-peak, and the full set of optically available light ($38 < Z < 56$) and heavy ($56 < Z < 92$) neutron-capture elements. These neutron-capture elements were not produced in the observed metal-poor stars themselves, but in a previous-generation SN explosion. The so-called r-process metal-poor stars formed from material that was chemically pre-enriched by this SN. We are thus able to study the “chemical fingerprint” of individual r-process events that likely occurred shortly before the formation of the observed star. Hence, the r-process stars fortuitously bring together astrophysics and nuclear physics by acting as a “cosmic laboratory” for both fields of study, and provide crucial experimental data on heavy-element production.

The picture that has been emerging from these observation is simple and yet astounding. The abundance patterns of the neutron-capture elements particularly the heaviest ones with $Z > 56$, agree extremely well with each other in all r-process stars (Barklem et al. 2005; Frebel et al. 2007a; Hill et al. 2002; Ivans et al. 2006; Johnson & Bolte 2001; Sneden et al. 1996) and with the scaled solar r-process pattern (e.g. Burris et al. 2000). Overall, this behavior suggests that the r-process is universal and leads to the same elemental ratios in the early Universe as at much later times, when the Sun was born⁵. The universality offers a unique constraint on any theoretical modeling of the r-process as the end-product is “known” through the r-process stars. It also enables calculating elemental ratios involving radioactive elements such as thorium and uranium that can be compared with observed measurements of the left-over radioactive stellar material. This, in turn, makes possible nucleochronometric age dating of the oldest stars.

Among the lighter neutron-capture elements there are abundance deviations between the scaled solar r-process pattern and to some extent among the individual stars. Since it is not clear if these lighter elements are produced by a single r-process, additional new processes were invoked in order to explain the entire spread of observed neutron-capture abundances in this mass range (e.g., Aoki et al. 2005; Travaglio et al. 2004; Wanajo & Ishimaru 2005). Suggestions include a “weak” r-process acting as a “failed” r-process only producing elements with $Z < 56$. An example of this process may be the r-poor star HD122563 (Honda et al. 2007 2006) showing a comparable, exclusive light neutron-capture element enhancement. Unraveling the exact details about the different r-processes should shed new light on the astrophysical site(s) of the r-process.

A “clean” r-process signature can only be observed in those stars that formed before the onset of the s-process ($[\text{Fe}/\text{H}] \sim -2.6$; Simmerer et al. 2004) and at times when the galactic inventory of lighter elements was still low so that spectral contamination with metal lines is minimal. Only the most metal-poor stars can thus be examined for the r-process signature. The first strongly enhanced r-process star was discovered more than a decade ago in the HK survey, CS 22892-052 (Sneden et al. 1996). A second star was found a few years thereafter, CS 31082-001 (Cayrel et al. 2001). Recognizing the need to find more such stars to enable detailed studies of the r-process, Christlieb et al. (2004) initiated a large campaign to observe metal-poor candidate stars from the main Hamburg/ESO survey. It led to the discovery of several strongly r-process-enhanced stars (Barklem et al. 2005; Hayek et al. 2009) and dozens of mildly enriched ones. Two more such stars were found more recently elsewhere (Frebel et al. 2007a; Lai et al. 2008).

The metallicity of all the strongly r-enriched stars is coincidentally $[\text{Fe}/\text{H}] \sim -3.0$ or just above it. Regarding their light-elements, no unusual abundances are found, and their halo-typical enhancements in α -elements suggest a core-collapse SN the source responsible for their overall elemental signature, including the neutron-capture elements. This is in line with SNe being the early contributors to galactic chemical evolution whereas AGB enrichment sets in only at somewhat later times due to their evolutionary timescales and the presence of seed nuclei (i.e., from Fe-peak elements created in previous SNe generations).

4.2 Nucleo-Chronometry of the Oldest Stars

The long-lived radioactive isotopes ^{232}Th (half-life of 14 Gyr) and ^{238}U (4.5 Gyr) are suitable for measurements of cosmic timescales. They also have transitions in the optical range so that, in principle, Th and U abundances can be measured in stellar spectra of r-enriched stars. However, suitable stars for these challenging measurements are difficult to find: Cool metal-poor red giants that exhibit very strong overabundances of r-process elements. Their carbon abundances should be low (i.e. subsolar) since CH features blend with many important neutron-capture lines (e.g. U, Pb), rendering them unmeasurable in carbon-rich r-process stars such as CS 22892-052. Moreover, the stars need to be bright (preferably $V < 13$) so that high-resolution data with very high S/N can be collected in reasonable observing times. Many neutron-capture features are very weak and often partially blended and thus require exceptionally high data quality. The two most important examples are the extremely weak U line at 3859 Å and the even weaker Pb line at 4057 Å. These two lines are the strongest optical transitions of these element. Subject to the availability of a very suitable star, a successful U measurement requires a $R > 60,000$ spectrum with a S/N of at least 350 per pixel at 3900 Å. A Pb measurement may be attempted in a spectrum with $S/N \sim 500$ at 4000 Å.

⁴ Stars with $[\text{r}/\text{Fe}] > 1.0$; r represents the average abundance of elements from the r-process.

⁵ The Sun’s r-process pattern can be obtained by subtracting the calculated s-process component from the measured total abundance pattern.

Fortunately, Th and several other stable r-process elements (most notably Eu) can be detected in lower S/N data, and have led to a number of stellar age measurements. Such ages can be derived from a ratio of a radioactive element to a stable r-process nuclei (i.e. Th/r, U/r, U/Th; with r being stable elements such as Eu, Os, and Ir), and comparing them with calculations of their initial r-process productions (e.g. Schatz et al. 2002). Since the giant CS 22892-052 is very C-rich, U could not be measured but its Th/Eu ratio yielded an age of 14 Gyr (Snedden et al. 2003). Johnson & Bolte (2001) measured similar ages of five mildly r-enriched stars, and other studies have produced ages of another few (Barklem et al. 2005; Cowan et al. 2002; Hayek et al. 2009; Lai et al. 2008; Westin et al. 2000).

Compared to Th/Eu, the U/Th ratio is more robust to uncertainties in the theoretically derived production ratio because Th and U have similar atomic masses (for which uncertainties would largely cancel out; e.g., Kratz et al. 2004; Wanajo et al. 2002). Hence, stars displaying Th and U are the more desired r-process stars. For a similar reason, stable elements of the 3rd r-process peak ($76 \leq Z \leq 78$) are best used in combination with the actinides (Th, $Z = 90$ and U, $Z = 92$). The first U detection was made in the giant CS 31082-001 (Cayrel et al. 2001) giving an age of 14 Gyr as derived from the U/Th ratio. Other chronometer ratios in this star, such as Th/Eu, however, yielded *negative* ages. This is due to unusually high Th and U abundances combined with an underabundance in Pb relative to the majority of r-process enriched metal-poor stars. By now, there are four known r-process stars (Hayek et al. 2009; Hill et al. 2002; Honda et al. 2004; Lai et al. 2008) with such high Th/Eu ratios ($\sim 20\%$ of r-process stars). Since only the elements heavier than the 3rd r-process peak are (equally) affected (Roederer et al. 2009), the U/Th ratio still gives a reasonable age in CS31082-01. This behavior was termed an “actinide-boost” (Schatz et al. 2002), but it has become clear that these stars likely have a different origin (Kratz et al. 2007) than “normal” r-process stars. It also supports the conjecture that there are multiple r-process sites (Hill et al. 2002).

Only one star has so far been discovered for which measurements of Th and U provide stellar age determinations from more than just one chronometer ratio. The giant HE 1523–0901 ($V = 11.1$) was found in a sample of bright metal-poor stars (Frebel et al. 2006) from the Hamburg/ESO Survey. It has the strongest enhancement in r-process elements so far, $[r/Fe] = 1.8$ (Frebel et al. 2007a), and among the measured neutron-capture elements are Os, Ir, Th, and U. In fact, the U detection in this star is currently the most reliable one of only *three* stars with such measurements (in CS31082-01, and a somewhat uncertain detection in BD +17° 3248; Cowan et al. 2002). Figure 5 shows the spectral region around the U line from which the U abundance was deduced. The averaged stellar age of ~ 13 Gyr (Frebel et al. 2007a) is based on seven chronometers Th/r, U/r and U/Th involving combinations of Eu, Os, Ir, Th and U.

Unfortunately, realistic uncertainties for any such age measurements range from ~ 2 to ~ 5 Gyr (see Schatz et al. 2002 and Frebel et al. 2007a for a discussion). Nevertheless, the stellar ages of old stars naturally provide an important independent lower limit to the age of the Galaxy, and hence, the Universe. The currently accepted value for the age of the Universe is 13.7 Gyr (Spergel et al. 2007), making these r-process stars some of the oldest known objects. This is in line with the low metallicities of the stars that already indicates a very early formation time.

In the absence of an age-metallicity relation for field halo stars, the nucleo-chronometric ages thus demonstrate that metal-deficient stars are indeed quite ancient, and well suited for studying the early Universe. By extension, this furthermore suggests that metal-poor stars with similarly low Fe abundances but no excess in r-process elements should also be old. Moreover, the commonly made assumption about the low mass (0.6 to $0.8 M_{\odot}$) of these long-lived objects is justified as well.

4.3 A Stellar Triumvirate: Th, U and Pb

Since different r-process models and the associated parameters usually yield different r-process abundance distributions, particularly in the heavy mass range, self-consistency constraints are very valuable. Explaining the stellar abundance triumvirate of Th, U and Pb can provide such constraints. These three elements are intimately coupled not only with each other but also to the conditions (and potentially also the environment) of the r-process. Pb is the β -plus α -decay end-product of all decay chains in the mass region between Pb and the onset of dominant spontaneous fission above Th and U. It is also built up from the decay of Th and U isotopes. Together with the Th and U measurements, a known Pb abundance provides important constraints also on those poorly understood decay channels. They are of critical importance for the successful modeling of the r-process which, in turn, could provide improved initial production ratios necessary for stellar age dating.

A new spectrum of HE 1523–0901 with $S/N \sim 500$ was recently obtained with VLT/UVES. Preliminary results indicate a detection of this extremely difficult line measurement with an abundance of $-0.4 < \log \epsilon(\text{Pb}) < -0.3$ (A. Frebel et al. 2010 in preparation). To learn about the different contributions to the production of lead, decay contributions of ^{238}U into ^{206}Pb , ^{232}U into ^{208}Pb , and ^{235}U into ^{207}Pb can be calculated (whereby the last one is based on a theoretically derived ratio of $^{235}\text{U}/^{238}\text{U}$). The total abundance of these three decays channels amounts to $\log \epsilon(\text{Pb}) = -0.72$ which leaves “room” for the direct and indirect decay channels that likely produce the main portion of the Pb in the star. Using r-process model calculations, predictions were derived for the total Pb to be found in HE 1523–0901. A site-independent model of the classical “waiting-point” approximation yielded $\epsilon(\text{Pb}) = -0.346$ (Frebel & Kratz 2009) for a decay time of 13 Gyr which is in agreement with the preliminary abundances. At the same

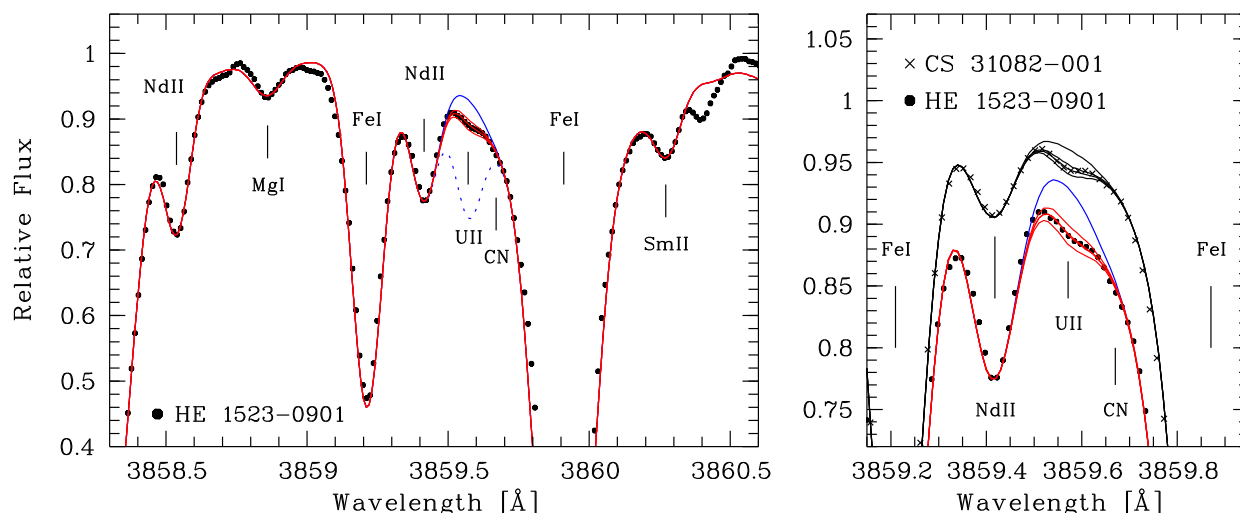


Fig. 5 Spectral region around the U II line in HE 1523–0901 (*filled dots*) and CS 31082–001 (*crosses*; right panel only). Overplotted are synthetic spectra with different U abundances. The dotted line in the left panel corresponds to a scaled solar r-process U abundance present in the star if no U decayed. Figure taken from Frebel et al. (2007a).

time, this prediction is less in agreement with the measured value of $\log \epsilon(\text{Pb}) = -0.55$ in CS31082-001 (Plez et al. 2004). This low Pb values is difficult to understand theoretically (despite the actinide boost and high Th and U), and is currently subject to much debate.

4.4 The s-Process Signatures

Neutron-capture elements are also produced in the interiors of low and intermediate-mass asymptotic giant branch (AGB) stars through the s-process and later dredged up to the surface. Unlike the r-process, the s-process is not universal because two different sites seem to host s-process nucleosynthesis. The “main” component of the s-process occurs in the helium shells of thermally pulsing lower mass AGB stars and is believed to account for elements with $Z \geq 40$ (e.g., Arlandini et al. 1999; Karakas et al. 2002). The so-called “weak” component occurs in the He- and C-burning cores of more massive stars, and preferentially produces elements around $Z \sim 40$.

The s-process leads to a different characteristic abundance pattern of neutron-capture elements than the r-process. The signature is also observed in some metal-poor stars, and their abundances follow that of the scaled solar s-process. The s-process metal-poor stars received their s-enriched material during a mass transfer event across a binary system from a former more massive companion that went through its AGB phase (e.g., Aoki et al. 2001; Bisterzo et al. 2009; Norris et al. 1997a). During this period, large amounts of carbon are also transferred to the companion producing a typical carbon-rich, s-rich metal-poor stellar signature. Some metal-poor stars display signatures from both r- and s-process enhancement in their abundance pattern (e.g., Barbuy et al. 2005; Cohen et al. 2003; Jonsell et al. 2006; Roederer et al. 2008). Several different scenarios have been

invoked to explain the combination of the two neutron-capture processes originating at two very different astrophysical sites. However, no unambiguous explanation has yet been found.

5 Tracing the Formation of the Galactic Halo with Metal-Poor Stars

Simulations of the hierarchical assembly of galaxies within the cold dark matter framework (Diemand et al. 2007; Springel et al. 2008) show that the Milky Way halo was successively built up from small dark matter substructures, often referred to as galactic building blocks, as long ago suggested by Searle & Zinn (1978). However, these simulations only include dark matter, and it remains unclear to what extent small dark halos contain luminous matter in the form of stars and gas. This question is particularly important with respect to the so-called “missing-satellite” problem which reflects the mismatch of the number of observed dwarf galaxies surrounding the Milky with the predicted number of substructures for a Milky Way-like halo. Studying the onset of star formation and associated chemical evolution in dwarf galaxies thus provides some of the currently missing information for our understanding of how the observed properties of small satellites relate to the dark matter substructures that build up larger galaxies.

5.1 Chemical Evolution of Dwarf Galaxies and their Connection to the Stellar Halo

The connection between the surviving dwarfs and those that dissolved to form the halo is best addressed by examining in detail the stellar chemical compositions of present-day dwarf galaxies. Establishing detailed chemical histories of these different systems can provide constraints on their

dominant chemical enrichment events, as well as the formation process of the Milky Way. Specifically, detailed knowledge of the most metal-poor (hence, oldest) stars in a given system allow insight into the earliest phases of star formation before the effects of internal chemical evolution were imprinted in stars born later with higher metallicity (for further details on this topic we refer the reader to the recent reviews by Tolstoy et al. 2009 and Koch 2009).

If the old, metal-poor halo was assembled from dwarf galaxies, the metallicities of stars in dwarf galaxies must reach values as low as (or lower) than what is currently found in the Galactic halo. Moreover, the abundance ratio of those low-metallicity stars must be roughly equal to those of equivalent stars in the halo. Assuming that the currently observable dwarf galaxies are the survivors of such an early accretion process, they provide an opportunity to examine their stellar chemistry in search for such an accretion process. Until recently, the common wisdom was, however, that the “classical” dwarf galaxies in the Local Group (e.g., Carinae, Sextans, Sculptor, and Fornax), would not contain any stars below $[\text{Fe}/\text{H}] = -3$ (e.g., Shetrone et al. 2003) despite the fact that many halo stars exist with such low Fe values, and even some with metallicities as low as $[\text{Fe}/\text{H}] \sim -5.0$. Furthermore, the higher-metallicity stars were found to have abundance ratios different from comparable halo stars. Most strikingly, the α -element abundances are not enhanced, indicating different enrichment mechanisms and timescales in these systems. This sparked a debate about the viability of the Searle & Zinn (1978) paradigm, and in trying to explain the origin of the metal-poor stellar halo. However, it has now been shown that this claim stems merely from biases in earlier search techniques (Cohen & Huang 2009; Kirby et al. 2009; Starkenburg et al. 2010). With improved methods for identifying the lowest-metallicity objects (e.g., Kirby et al. 2008), extremely metal-poor stars with $[\text{Fe}/\text{H}] < -3$ have already been identified in several dwarf galaxies (Frebel et al. 2010; Geha et al. 2009; Kirby et al. 2008; Norris et al. 2008).

Ultra-Faint Dwarf Galaxies

Kirby et al. (2008) extended the metallicity-luminosity relationship to the ultra-faint ($L < 10^5 L_\odot$) dwarfs and showed that the lowest luminosity dwarfs have indeed the lowest average metallicities, with several individual stars having $[\text{Fe}/\text{H}] < -3$. The combined MDF of all these systems goes down to $[\text{Fe}/\text{H}] \sim -3.3$, and the shape appears similar to that of the Milky Way halo. The ultra-faint dwarf galaxies have large internal metallicity spreads, confirming earlier results at lower spectral resolution (e.g., Simon & Geha 2007, Norris et al. 2008). They span more than 1 dex in $[\text{Fe}/\text{H}]$ in some of them. Such spreads indicate early star formation in multiple proto-dwarf galaxies that later merged, extended star formation histories, or incomplete mixing in the early ISM, or all of the above.

The three brightest stars in each of Ursa Major II (UMa II) and Coma Berenices (ComBer) and two stars in Hercules are the first stars in the ultra-faint dwarf galaxies

to have been observed with high-resolution spectroscopy. Two of them (in UMa II) are also the first known extremely metal-poor stars which are not members of the halo field population. Details on the observations and analysis techniques are given in Frebel et al. (2010) and Koch et al. (2008). For the UMa II and ComBer stars, chemical abundances and upper limits of up to 26 elements were determined for each star. The abundance results demonstrate that the evolution of the elements in the ultra-faint dwarfs is very similar to that of the Milky Way, and likely dominated by massive stars. The α -elements in these two ultra-faint dwarf stars are overabundant, showing the halo-typical core-collapse SNe signature. This is the first evidence that the abundance patterns of light elements ($Z < 30$) in the ultra-faint dwarfs are remarkably similar to the Milky Way halo. The agreement suggests that the metal-poor end of the MW halo population could have been built up from destroyed dwarf galaxies. Similar abundance results were also found by other studies (Feltzing et al. 2009; Norris et al. 2010; Simon et al. 2010) but also indications that the chemical evolution in these small systems may have been very inhomogeneous.

The neutron-capture abundances are extremely low in the ultra-faint dwarf stars. The observed Sr and Ba values are up to two orders of magnitude below the abundances found in typical MW halo stars with similar Fe content. However, a very large spread (up to 3 dex) in these elements is found among halo stars themselves. The large depletions in the dwarf galaxy stars are thus not inconsistent with the halo data since similarly low values are found in numerous objects. Interestingly though, the low neutron-capture abundances may represent a typical signature of stars in dwarf galaxies. Similarly low values are also found in Hercules (Koch et al. 2008) and Draco (Fulbright et al. 2004) despite their sometimes relatively high Fe values of $[\text{Fe}/\text{H}] \sim -2.0$ (in Hercules).

“Classical” dSphs

By applying the new search techniques also to the more luminous dwarf galaxy Sculptor, the first extremely metal-poor star in a classical dwarf was recently discovered (in a sample of 380 stars; Kirby et al. 2009). The metallicity of $[\text{Fe}/\text{H}] \sim -3.8$ was confirmed from a high-resolution spectrum taken with Magellan/MIKE (Frebel et al. 2009b). Only nine stars in the halo have even lower Fe abundances than this object. This remarkable finding suggests that more such low-metallicity stars could soon be identified in the more luminous systems (see also Starkenburg et al. 2010). The new star also shows that a metallicity spread of ~ 3 dex is present in Sculptor. The chemical abundances obtained from the high-resolution spectrum reveal a similar picture to what has been found in the ultra-faint dwarf stars. The Sculptor star, at $[\text{Fe}/\text{H}] \sim -3.8$, also has a remarkably similar chemical make-up compared to that of the Milky Way halo at the lowest metallicities. This is in contrast to what is found at higher metallicities in these brighter dwarfs which have lower α -abundances than comparable halo stars (e.g., Geisler et al. 2005; Shetrone et al. 2003). There is in-

creasing evidence, though that a transition of halo-typical abundance ratios may take place around a metallicity of $[\text{Fe}/\text{H}] = -3.0$ (Aoki et al. 2009; Cohen & Huang 2009).

5.2 The Origin of the Metal-Poor Tail of the Halo

These new observational results are broadly consistent with the predictions of currently favored cosmological models (e.g. Robertson et al. 2005, Johnston et al. 2008). The majority of the mass presumably in the inner part of the stellar halo (at $[\text{Fe}/\text{H}] \sim -1.2$ to -1.6) was formed in much larger systems such as the Magellanic Clouds. A scenario where the ultra-faint dwarf galaxies contributed some individual metal-poor stars that are now found primarily in the outer Galactic halo (although not exclusively) is supported. However, these systems may not have been sufficiently numerous to account for the entire metal-poor end of the Fe metallicity distribution of the Milky Way halo. Since the classical dSphs have more stellar mass and have been shown to also contain at least some of the most metal-poor stars (Frebel et al. 2009b; Kirby et al. 2009), they could have been a major source of the lowest-metallicity halo stars. Additional observations of more extremely metal-poor stars in the various dwarf galaxies are highly desirable in the quest to determine individual MDFs for each of these galaxies, and how those would compare with each other and the Milky Way.

6 Outlook – What is Possible with Stellar Archaeology?

Old metal-poor stars have long been used to learn about the conditions of the early Universe. This includes the origin and evolution of the chemical elements, the relevant nucleosynthesis processes and sites and the overall chemical and dynamical history of the Galaxy. By extension, metal-poor stars provide constraints on the nature of the first stars and their initial mass function, the chemical yields of first/early SNe, as well as early star and galaxy formation processes including the formation of the galactic halo. Finding more of the most metal-poor stars (e.g., stars with $[\text{Fe}/\text{H}] < -5.0$) would enormously help to address all of these topics in more detail. However, these stars are extremely rare (Schörck et al. 2009) and difficult to find. The most promising way forward is to survey larger volumes further out in the Galactic halo.

But how feasible is it to identify stars with even lower metallicities? Frebel et al. (2009a) calculated the minimum observable Fe and Mg abundances in the Galaxy by combining the critical metallicity of $[\text{C}/\text{H}]_{\text{min}} = -3.5$ (the criterion for the formation of the first low-mass stars by Bromm & Loeb 2003) with the maximum carbon-to-iron ratio found in any metal-poor star. The resulting minimum Fe value is $[\text{Fe}/\text{H}]_{\text{min}} = -7.3$. Analogously, the minimum Mg value is $[\text{Mg}/\text{H}]_{\text{min}} = -5.5$. If $[\text{C}/\text{H}]_{\text{min}}$ was lower, e.g.,

$[\text{C}/\text{H}]_{\text{min}} = -4.5$, as suggested by recent dust cooling computations, the minimum observable Fe and Mg abundances would accordingly be lower. Spectrum synthesis calculations suggest these low abundance levels are indeed measurable from each of the strongest Fe and Mg lines in suitably cool metal-deficient giants.

Future surveys such as Skymapper and LAMOST will provide an abundance of new metal-poor candidates as well as new faint dwarf galaxies. By accessing such stars in the outer Galactic halo and dwarf galaxies we will be able to gain a more complete census of the chemical and dynamical history of our own Galaxy. Also, the lowest metallicity stars are expected to be in the outer halo (e.g., Carollo et al. 2007). Their corresponding kinematic signatures may prevent them from accreting too much enriched material from the ISM during their lives so that their surface composition would not be altered (i.e., increased; Frebel et al. 2009a). Hence, selecting for the most metal-poor candidates will increasingly rely on our ability to combine chemical abundance analyzes with kinematic information. Future missions such as GAIA will provide accurate proper motions for many object that have no kinematic information available, including for most of the currently known metal-poor giants.

However, many, if not most, of these future metal-poor candidates will be too faint to be followed up with the high-resolution spectroscopy necessary for detailed abundance analyzes. This is already an issue for many current candidates leaving the outer halo a so far largely unexplored territory: The limit for high-resolution work is $V \sim 19$ mag, and one night's observing with 6-10 m telescopes is required for the minimum useful signal-to-noise (S/N) ratio of such a spectrum. With the light-collecting power of the next generation of optical telescopes, such as the Giant Magellan Telescope, the thirty Meter Telescope or the European ELT, and if they are equipped with high-resolution spectrographs, it would be possible to not only reach out into the outer halo in search of the most metal-poor stars, but also provide spectra with very high- S/N ratio of somewhat brighter stars. For example, r-process enhanced stars which provide crucial empirical constraints on the nature of this nucleosynthesis process require exquisite data quality e.g. for uranium and lead measurements that are currently only possible for the very brightest stars.

It appears that the hunt for the metal-deficient stars in dwarf galaxies may have just begun since these dwarfs host a large fraction of low-metallicity stars, perhaps even much higher than what has so far been inferred for the Galactic halo (Schörck et al. 2009). The detailed abundance patterns of the stars in UMa II, ComBer, Leo IV and Sculptor are strikingly similar to that of the Milky Way stellar halo, thus renewing the support for dwarf galaxies as the building blocks of the halo. Future discoveries of additional faint dwarf galaxies will enable the identification of many more metal-poor stars in new, low-luminosity systems. But also the brighter dSphs have to be revisited for their metal-poor

content (Kirby et al. 2009). More stars at the lowest metallicities are clearly desired to better quantify the emerging chemical signatures and to solidify our understanding of the early Galaxy assembly process. Together with advances in the theoretical understanding of early star and galaxy formation and SNe yields, a more complete picture of the evolution of the Milky Way Galaxy and other systems may soon be obtained. Only in this way can the hierarchical merging paradigm for the formation of the Milky Way be put on firm observational ground.

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Appendix

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